Wind Turbine Noise: Psychoacoustics to the Rescue

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ABSTRACT

With respect to communities in proximity to wind farm installations, the degree of noise complaints when compared to socio-acoustic studies of various noise sources in the wider community reveal a statistical anomaly that cannot be ignored. Various acousticians investigating the community response to wind turbine noise, after the event, have indicated dose-response curve noise targets to be lower than that nominated by Environmental Authorities. With the increase in the capacity of wind turbines there is a greater area of affectation and as such higher proportion of the community being impacted. Acoustic researchers working with the end product (the residents) have identified unique acoustic signatures related to wind turbines which are significantly different to road traffic noise and therefore question the limits imposed for wind turbines. To address the issue of wind turbine noise there are various investigations being undertaken to get to the bottom of the problem that in turn may then require medical investigations to determine the cause of the impacts on the community. Acousticians working with the community over the issue of wind turbine noise impacts are basing their investigations from the principles of psychoacoustics. A number of those investigations are discussed.

1. INTRODUCTION

In 2011 the author was requested to undertake a peer review of a proposed wind farm in a rural area in the state of NSW (in Australia) that resulted in questions as to appropriate criteria and assessment procedures (that involved non—standard acoustic procedures) when compared with general environmental noise assessments associated with the industry.

As a result of the author's investigations it was apparent there was no scientific or medical bases for the nominated noise criteria for industrial wind farms, but a "borrowing" of acoustic criteria from other noise sources. At that time, the author formed the view that it was necessary to identify and "acoustic signature" associated wind turbines from which one could undertake proper medical studies.

Following the presentation of a hypothesis for investigating health impacts associated with wind turbines [1] further monitoring and research has been undertaken into identifying the acoustic spectrum (including info sound) of emissions from operational turbines.

In the intervening period monitoring has been undertaken (in Australia) in proximity to a number of wind farms that identified the acoustic signature of wind turbines was entirely different to that of general environmental or industrial noise [2,3].

In all cases a distinct acoustic signature was observed that is not found in the natural environment. When the turbines are operating it was established that a periodic pattern in the infrasound region (below 20 Hz) was present but the same pattern was not present in the natural acoustic environment when the turbines were not operating.

Further research into windfarm noise identified the periodic pattern in the & region was as the result of pulsations emitted by the turbines and technical issues arising from the digital analysis of those pulsations. Those investigations questioned whether the assessment procedures or analysis that had been nominated for wind turbines were appropriate.

In late 2013 the author was approached by wind farm operator to undertake noise monitoring at the Cape Bridgewater wind farm in an effort to identify the basis of complaints from residents that were related to a "compliant windfarm". Specifically, the wind farm operator had had noise monitoring undertaken using the general dB(A) parameter and was unable to resolve complaints from local residents.

Following a meeting with the six nominated affected residence a proposal was presented to undertake a study involving all parties, was to be transparent, not restricted to just noise complaints, and required the full cooperation of both the residence and the wind farm operator. The author did not expect to be given a brief to undertake the work.

However subject to certain constraints the author was engaged in 2014 by the operator of the Cape Bridgewater wind farm to undertake a specific investigation into complaints related to the Cape Bridgewater wind farm.

The investigation it Cape Bridgewater involved extensive testing and analysis, leading to the issue of report in January 2015 [4]. The results of that investigation have led to further research into wind turbine noise, with some of the noise data from that project still being used by the author (with the consent of residents to use the data) in current research.

The Cape Bridgewater study report provided the results of an investigation which is a typical to that provided in an acoustic report accompanying an application for a wind farm project, because it was an investigation of long-standing noise complaints rather than a predicted (noise) Impact assessment prior to construction of a wind farm.

The Cape Bridgewater study commenced on the basis of the wind farm operator acknowledging disturbances reported by residents who had formed the view that disturbances came from the wind farm.

The Cape Bridgewater wind farm study did not look at acoustic compliance of the subject wind farm but had a specific brief to ascertain the operation of the wind farm relative to the disturbance reported by the residents and to ascertain if certain sound levels or wind speeds were related to those disturbances.

The Cape Bridgewater investigation therefore commenced from the perspective of complaints by residents in proximity to the wind farm. The study considered the impact reported by residents in proximity to a wind farm related to the noise levels that were measured during the study period.

The available funding provided by the wind farm operator covered the field work, some of the analysis of the data and some of the report.

The majority of the analysis and the preparation of the report was funded by me as the funding from the wind farm operator could not complete the second part of the brief and extensions to the funding were rejected by the wind farm operator.

The project brief for the Cape Bridgewater investigation of starting from the complainant's end of the question to identify the source acoustic signals/impacts follows the principles of a "Soundscape" investigation and was not a compliance test. In fact, the operator of the wind farm specifically prohibited me from undertaking a compliance test. The Cape Bridgewater study has since been identified as the first Soundscape study of a wind farm.

The Cape Bridgewater wind farm noise study has been the subject of discussion in acoustic circles around the world and I expect material from that study that may be presented to the Court may or may not be taken out of context.

The Cape Bridgewater wind farm study **did not look at acoustic compliance** of the subject wind farm but had a specific brief to ascertain the operation of the wind farm relative to the disturbance reported by the residents and to ascertain certain sound levels or wind speeds related to those disturbances.

As a result of the Cape Bridgewater study report the author was invited to become a member of the acoustic Society of America's wind turbine working group. At the request of the working group the author has undertaken further research into wind turbine noise that in turn led the author into undertaking research into what has become a fascinating area of acoustics previously unknown, that being the area of psychoacoustics and subjective assessment (of wind turbine noise).

2. PREVIOUS ACOUSTIC RESEARCH IN RELATION TO WIND FARM NOISE

In the process of seeking to establish the basis of why the community in proximity to wind farms are experiencing adverse impacts (including in the majority of cases sleep disturbance) has required the author to re-evaluate the application of general acoustic measurement and analysis procedures. In that process important work undertaken by previous investigators in both wind turbine noise and psychoacoustics (that in mainstream acoustics may appear to have been forgotten) has played an important part in joining the dots as to how acousticians using psychoacoustics can play an important role in protecting the health and well-being of communities in proximity to wind farms. That research work in turn can lead to appropriate acoustic criteria to protect those residents from adverse impacts.

In the 1980's NASA (National Aeronautics and Space Administration) undertook pioneering acoustic work under a program for developing wind turbines [5, 6].

As a student of psychoacoustics, it is worthwhile reviewing the work undertaken by the US Department of Energy under the leadership of Dr Kelley and in particular the pioneering work with respect to the Mod-1 turbine [7].

NASA developed a number of horizontal axis 2 bladed downwind turbines commencing with first generation machines (Mod-0 and Mod-0A), involving a 100 kW and a 200 kW unit, respectively. The Mod-0 turbines were not considered to create significant noise [8].

The Mod-1 project was initiated in 1974 based on the Mod-0 results and involved the construction of a 200 ft diameter wind turbine with a rated power of 2000 kW. At the time, the turbine represented the largest in the world. The Mod-0 and Mod-1 turbines were developed with the turbine blades being downwind of the tower structure, which was a lattice type construction.

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The Mod-1 turbine resulted in noise complaints to a small fraction of families living within a 3 km radius of the turbine. A detailed investigation was undertaken by the Solar Energy Research Institute ("SERI") for the US Department of Energy [7].

Kelley et al. [7] identified the acoustic pulsations emitted from the Mod-1 turbine, the level of sound above human perception thresholds and the excitation of building/room modes in dwellings.

The Executive Summary of the SERI report [7] identified the perception of the complaints for the single Mod-1 turbine. The description of the complaints/impacts for the Mod-01 turbine are similar to that obtained for current wind farm (multiple wind turbine) installations. The key findings in the SERI report were **that the annoyance was real and not imagined, and the source of the annoyance was aerodynamic, that involved the passage of the turbine blades through the lee wakes of the large, 0.5 m cylindrical tower legs. In some instances, the acoustic impulses transmitted through the air were being focused on the complainant's homes, as a consequence of ground reflection and refraction by the atmosphere.**

As a result of the Mod-1 acoustic issues, the design of the NASA turbine program moved to the use of upwind turbines, starting with Mod-2, where the turbine blades were positioned in front of a circular tower.

From the Mod-1 turbine investigations, Kelley examined several acoustic metrics for assessing the interior low frequency annoyance [9], considering the overall degree of annoyance, any sensations of vibration or pressure or the sensing of any pulsations. Kelley proposed the use of the LSL or low frequency sound level weighting [10] or the C-weighting.

Kelley's proposal was not adopted by authorities (who have in general remained with dB(A) levels) although Jakobsen [11] proposed an internal low frequency parameter $L_{pA,\ LF}$ as the A-weighted level, in the frequency range of 10-160 Hz. The Jakobsen limit is used in Denmark.

The Kelley material undertook a psychoacoustic approach to addressing wind turbine noise, noting that at the time there were no acoustic criteria for wind turbines.

The UK assessment in the mid 1990 that produced ETSU-R-97 [12] was not based on any psychoacoustics investigations of wind turbine noise, but "borrowed" noise targets from research, principally on road traffic noise [13]. The ETSU-R-97 approach has been incorporated (in Australia) into various guidelines or Standards used to "assess" wind farms [14-17].

The nature of noise emitted from wind farms is not one of a steady noise but is subject to a significant variability in the noise emitted from a site by reason of the need for wind to drive the turbines and that there is a significant variability in the strength and direction of wind throughout the day/month/seasons of a year.

Therefore, the determination of acoustic impacts from operational wind farms will have a wide range of operating scenarios that at times may give rise to negligible impact whilst at other times may give rise to significant adverse impact. The use of averaging sound levels from wind farms over periods of time in which there can be dramatic differences in the power output of a wind farm, or could be occurring under relatively low power outputs leads to an acoustic averaging technique that fails to address the occurrence of adverse impacts on the community.

The interaction of individual turbines in a wind farm and the topography of a wind farm site changes the inflow air to turbines from the general acoustic analysis (at the development proposal stage) that assumes free flowing air at each turbine. The consequence of the absence of free flowing air and the disturbed air after a turbine that in turn can affect down wind turbines is commonly expressed as "wake" disturbance. The wake disturbance can give rise to significant changes in the acoustic signature of the wind farm at distances well removed from the wind farm site, and would appear to provide a severe limitation on the available power output of a wind farm when compared with the stated nominal "capacity" of a wind farm [18].

In seeking to reproduce an accurate acoustic signal of a wind farm for subjective testing, in view of the wide range of frequencies that have been identified, previous subjective testing has needed as array of speakers. The majority of the previous subjective testing has utilized a mono sound signal [19].

With respect to producing an accurate sound signal for subjective testing there are issues with reproducing the dynamic signal of the pulsations that are emitted from turbines.

Part of our earlier investigations into infrasound and pulsations from wind turbines was determining if the digital analysis was reflecting the actual audio signal that was there. As a result of those investigations we established issues with sample rates of Wave files and limitations in the upper limit of frequencies for sampling that could not reproduce the signal obtained in the field. Hence general instrumentation such as sound level meters have limited value in obtaining a suitable sound signal for subjective analysis of wind farm noise.

A principal concept to be absorbed in undertaking psychoacoustic assessments is that wind turbines do not produce infrasound as a sound in the normal sense of sound as tones. The digital analysis of wind turbine noise produces a signature in the infrasound region of the blade pass frequency (typically around 0.85 Hz – three blades at 17 rpm) and harmonics of that frequency, because the time signal has a periodic pulse every 1.18 seconds. The inverse of 1.18 seconds is 0.85Hz.

For a constant 100 Hz tone, a frequency analysis will give a peak at 100Hz and smaller peaks (in amplitude) at 200Hz, 300Hz, 400Hz.

If the tone is controlled so that the 100Hz tone is on for 900 ms (0.9 seconds) then off for 100ms and then that process is repeated constantly, then there will be two periodic functions in the time signal. One signal is the 100 Hz tone (with its harmonics) and another signal is the periodic function of 1 Hz (1 second). BUT there is no actual 1 Hz tone [20-22].

Wind turbines produce a broad band noise, but that noise varies in strength at the rate of the blade pass frequency. This variation of the noise level can be described as "modulation". In the wind industry it has been incorrectly called amplitude modulation.

Undertake digital analysis of the signal of broad band noise that is modulated at the 0.85Hz rate and the frequency analysis of the periodic function will show an infrasound signature – but it is not an infrasound "sound".

Swinbanks [23] identified digital filters have time constants that under standard filter theory cannot give the correct pressure levels for the very short durations of the pulses. The pulsating nature of the wind turbine noise does not permit the analysis of those transient signals to satisfy the fundamental filter formulae of BT=1 (bandwidth of the filter (Hz) times the analysis time (seconds) = 1) and causes the digital filters to overload (or ring at the relative filter frequency that is related to the rate of the pulsations).

In our laboratory for re-creating wind turbine noise, a wall of speakers (12 x 15" sub woofers each of 1000w rms capability) were placed in the chamber aperture and powered by D class amplifiers. We produced a crystal clear pure sine wave at 1 Hz of 96 dB (second harmonic down 27 dB) and 106 dB of crystal clear sine wave at 10 Hz. The chamber was used for determining the threshold of sensation versus threshold of hearing (the start of our psychoacoustic experiments) [24]. We confirmed the dip in the lower region of the hearing response presented by Watanbe and Moller [25].

Take the wind turbine noise signal and reproduce the signal in a laboratory, but place a filter in the sound system so that there are no signals going to the speakers below 20 Hz, one finds that as the wind turbine signal still pulsates the digital analysis of the signal reveal infrasound components. This is because the broad band sound that was left in our samples (limited to above 20Hz) was being modulated at a 0.85 Hz rate.

We used that facility to show that persons sensitized to wind turbine noise could detect the presence of the signal even when it was inaudible [26].

Prof Alec Salt showed the outer hair cells of the inner ear sensed infrasound [27] We provided Prof Salt high quality wave file samples of wind turbine noise with the above explanation of the modulation of the broad band sound. When Prof Salt applied those signals, he found the same response, i.e. you did not need to have actual infrasound to get the result. The outer hair cells were responding to the modulation. Prof Salt explained that the detection system in the ear is more susceptible to an asymmetric time signal. The pulsation of the wind turbine signal has a high crest factor but is not a symmetric signal on either side of the peak [28].

Considering the presence of a modulation of the broad band noise in the turbine signature and the result of Prof Salt's research ended up with the response of the hearing mechanism to what Zwicker and Fastl [29] identified as "fluctuation". The combination of the findings of these three professors has motivated the author's investigations in the use of the modulation index that is commonly referred to in the UK for an assessment of "enhanced amplitude modulation" of wind turbines.

Before moving into current research into modulation index of wind turbine noise one needs to consider for subjective testing the sound field that is generated.

In the realm of psychoacoustics, we do not live or hear in a mono world. Listening to wind turbine noise in stereo (using speakers or headphones) gives rise to an entirely different sound experience when compared to mono. The degree of subtlety in detecting the audible changes in wind turbines for a stereo signal versus a mono signal (typically obtained from a sound level meter) has to be experienced to appreciate limitations in previous subjective experiments of wind turbine noise.

With the identification of the pulsations of wind turbine noise and there is no longer the need to reproduce a test signal down to 0.5 Hz now permits subjective testing to be undertaken in smaller spaces. Using our small anechoic room and line array speakers (with subwoofers) eliminates the need for the use of the transmission loss chambers [26].

Applying the use of stereo recordings in investigating noise disturbance has led to some amazing results.

One example is the assessment of noise from patrons using a commercial adventure park involving noise generated by participants conducting tree climbing, elevated rope walking, flying fox/zip lines – all adjacent a residential area. The nature of the noise is one of multiple different transient noise events at or above the background noise level.

Utilizing three channel recordings to provide a time synched mono signal and a stereo signal that are then assessed with reference to the time trace from the mono signal has repeatedly found the stereo recording to identify around twice as many events as that obtained from the mon recording for the same sample.

3. CURRENT RESEARCH

In the Cape Bridgewater study, a hypothesis was presented in relation to disturbance detected/felt by residents involved in the study was that changes in the power output of the wind farm related to those disturbances.

Comparing the diaries of the residents involved in that soundscape study with the recorded data found there were four scenarios in the operation of the wind farm that were associated with significant levels of disturbance that being:

- when the turbines were seeking to start
- when the turbines were subject to winds strengths well above that associated with the maximum power output of the individual turbines
- when the wind farm was subject to a progressive increase in output power that exceeded 10%.
- when the wind farm was subject to a progressive decrease in output power that exceeded 10%.

Schomer [30] proposed a method of comparing windfarm noise disturbance onset time with the power output of the wind farm to be one of the recommendations of the Acoustical Society of America Wind Turbine Working Group. That exercise was undertaken by Morris and Cooper [31] identifying the occurrence and types of disturbance reports by the residents.

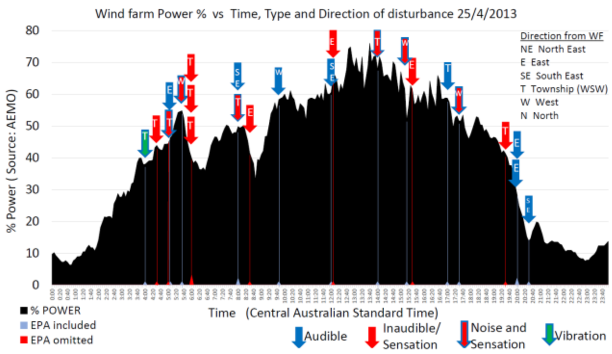

Figure 1 Waterloo wind farm power output resident's diaries

The first approach taken in assessing the impacts on residents presented in this paper is to marry the power output traces of the wind farm with the changes in the modulation indices at the time of the reported disturbances.

In Aachen last year [32] I presented a simplified method to assess the modulation of wind turbines by expanding the UK concept for EAM [33, 34] to undertake a 1/3 octave band statistical analysis of a 10 minute sample to provide the L1, Leq and L90 levels. For the purpose of determining the modulation index by the alternative method we determined the difference between the L1 and the L90 level. The L1 – L90 value was used as in Australia our environmental authorities refer to those parameters. One could adopt the difference between the L5 and the L95 as used in Japan and the UK.

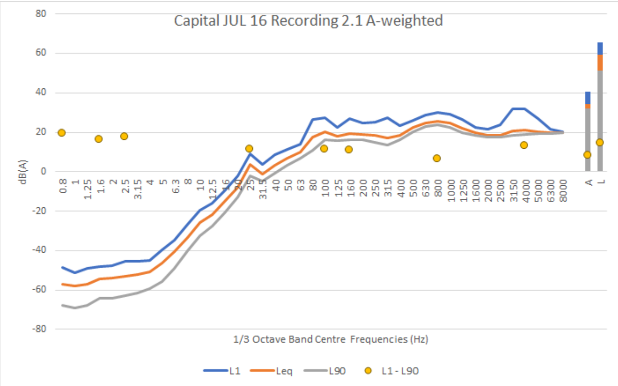

Figure 2: Amplitude Modulation derived from alternative method

The sample in Figure 2 above relates to an external measurement from the Capital wind farm (located about a three-hour drive south-west of Sydney, in Australia). At the position the nearest turbine is approximately 800 m whilst there are additional turbines that at times impact upon the noise monitoring location in the order of 1200 to 1600 m from the monitoring location.

The results in Figure 2 are A-weighted one third octaves as that is the preferred method used in the UK.

However as a result of our work and the need to identify the frequency of the fluctuations it is preferable to present the results as linear (un-weighted) spectra that is shown in Figure 23 below.

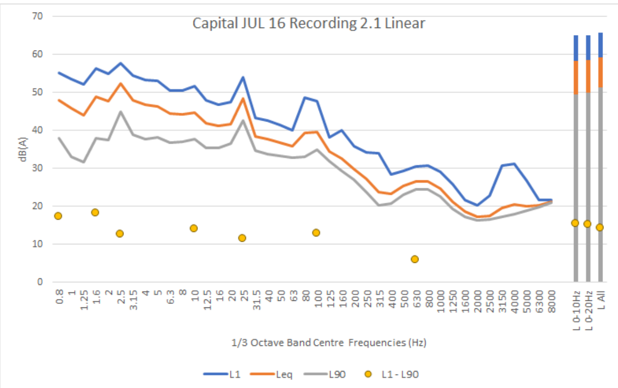

Figure 3: Linear (Unweighted) statistical results and Modulation Index

The application of the simplified modulation assessment identified above permits the reanalysis of wave files in an extremely time efficient manner that when applied to the Cape Bridgewater study produced a significantly greater number of datasets correlating with the hypothesis from that study, when compared using the assessment methodology applied in 2014.

The second approach taken in the assessment of wind turbine disturbance has been to utilize the results of sleep monitoring of individuals that is then compared with the power output of the wind farm and subsequently assessed in terms of the modulation index. This approach has led to a higher correlation between sleep disturbance and the operation of a wind farm.

Figure 4 presents a sample of monitoring over a night in which the red vertical lines relate to distinct instances of sleep disturbance that are then compared with the change in the power output of the wind farm in both actual change and absolute change that are then compared with the linear modulation index for the individual 10 minute samples throughout the night. For comparison with the UK/Japanese method both the L1 minus L90, and the L5 minus L95 are shown.

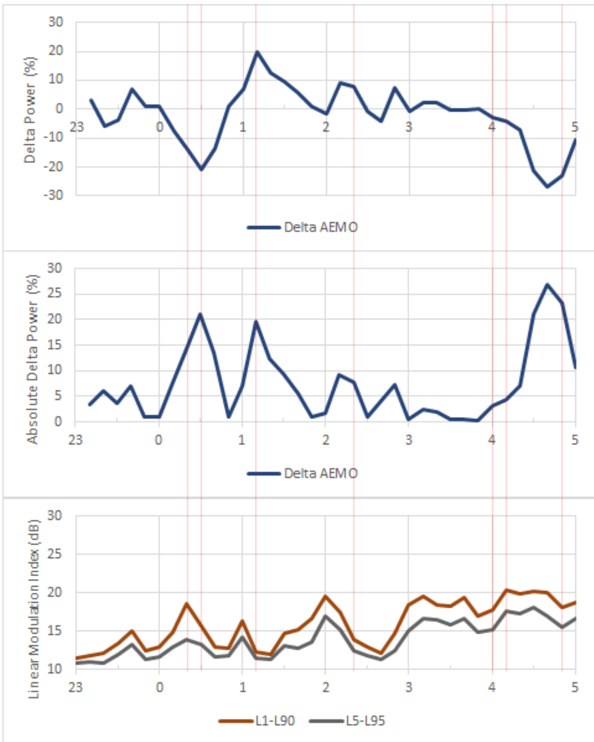

Figure 4: Power Output and Modulation Indices

It must be noted that the modulation index provided in Figure 4 relates to an indoor measurement as that is the situation for which disturbance is being considered. Accordingly, the attenuation of the high-frequency components (when compared to an external location) is significant.

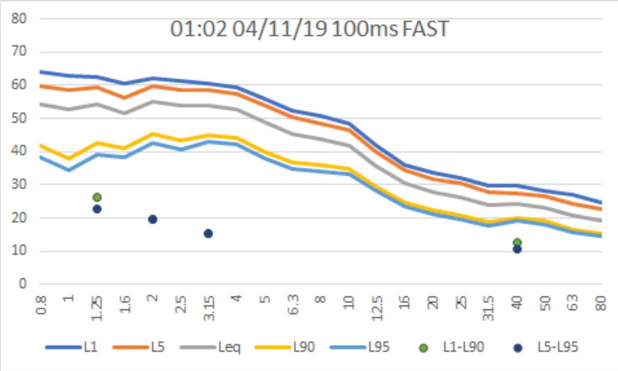

Figure 5: Modulation Indices at 1am

Figure 5 provides an example of the modulation index of obtained as a result of the significant change in power output around 1 am, noting that with respect to the second harmonic of the blade pass frequency of the turbines when assessed in one third octave band measurements there is a modulation index significantly higher than that obtained by an assessment of the linear level shown in Figure 4.

As a cross check exercise, we have undertaken the exercise set out in Figure 4 part without prior knowledge of sleep disturbance. After the exercise was undertaken for a number of nights when checking the sleep disturbance results there was a high level of agreement.

It is noted that the above measurements are reference to identification of the disturbance when utilizing environmental criteria that is expressed using FAST response and typically 100 ms sample rates.

I propose a fundamental hypothesis that by using the approach of identifying disturbance by residents that is associated with the operation of a wind farm and then undertaking the acoustic analysis to ascertain the change in the acoustic signature then the modulation index method permits an assessment from the perspective of psychoacoustics to determine the degree of fluctuation that has occurred to which the hearing mechanism may sense rather than hear.

However, the challenge to provide an adjustment to the measured levels to account for the presence of fluctuation requires one to consider two variables in determining the annoyance correction as a result of the actual measurements.

Zwicker and Fastl [29] have identified that the degree of annoyance is a function of the modulation depth and also a function of the frequency of the modulation. For fluctuation, the critical frequency of modulation is 2 hertz.

When one applies the function of the frequency of the modulation for the assessment of annoyance it would then appear that the level of modulation at the third and fourth harmonics of the blade pass frequency may be the controlling factor in the level of annoyance to which then one applies the difference in the depth of modulation to quantify the level of annoyance.

4. CONCLUSIONS

The use of noise criteria specified by regulatory authorities for the assessment of wind turbine noise that has been “borrowed” from non-wind turbine noise sources does not have the appropriate factual basis to protect the amenity of residents who are adversely impacted by the operation of wind turbines.

In order to quantify the level of disturbance from the operation of wind turbines it is necessary to determine the acoustic characteristics of the wind farm, for different operating scenarios, that give rise to disturbance.

To obtain the necessary data requires measurements of residents whilst experiencing disturbance and noise measurements to ascertain the acoustic signature.

Research work undertaken by the author has identified that residents are able to detect the operation of the wind farm without necessarily hearing any noise or having to view the wind turbines. The nature of the detection of inaudible wind turbine noise was considered as a concept in 2014 related to sensation.

Since that time additional work in quantifying the acoustic signature of wind turbine noise and the “discovery” of the work by Zwicker and Fastl in relation to fluctuation has created a new line of investigation to place in context the pulsating nature of the acoustic signature of wind turbines with respect to fluctuation.

By the use of the alternative modulation index method and comparing the 1/3 octave band statistical results with the change in power output of operational wind farms has supported the original hypothesis as to disturbance proposed by the author in the Cape Bridgewater study report.

Recent investigations that have included sleep monitoring has supported the hypothesis derived from the Cape Bridgewater study and provides measurable and repeatable results to the recommendation provided by Schomer at the June 2017 meeting of the Acoustical Society of America Wind Turbine Working Group [30].

This promising work from the perspective of psychoacoustics, when coupled with further sleep studies and determination of an appropriate ranking of disturbance may provide the necessary annoyance correction to be added to measured noise levels to protect the acoustic amenity of communities in proximity to wind farms.

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